NASA's Certification and Qualification Strategies for Additively Manufactured Hardware: Reuse and Challenges

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Materials Challenges in Reusable Liquid-Propellant Rocket Engines
Aerospace Corporation, El Segundo, CA
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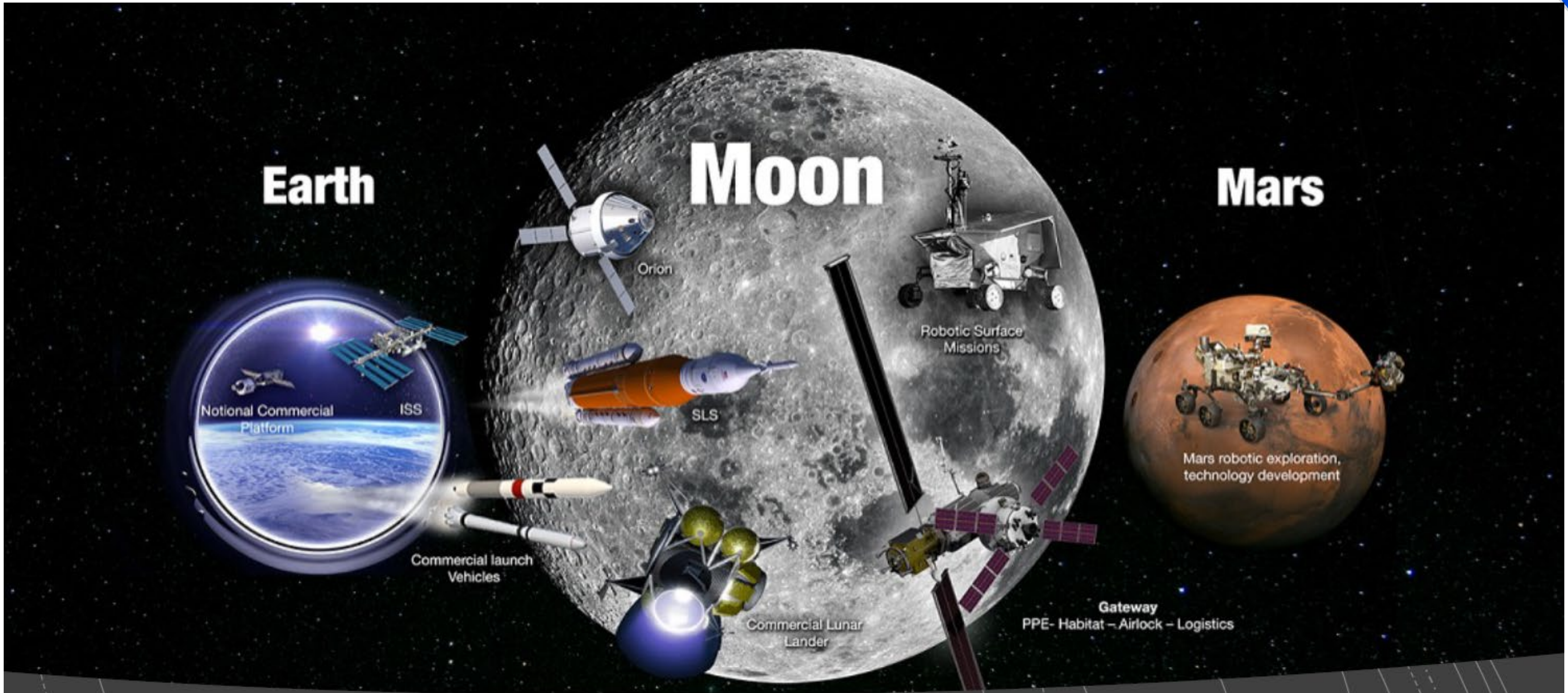


Exciting time at NASA with a lot of activities around Earth Orbit, getting ready to go to the Moon with eyes on Mars

Additive Manufacturing at NASA

- Fully embraces advantages of AM
  - Cost/lead time/part count reduction, new design and performance opportunities, rapid design-fail-fix cycles
- While fully understanding the challenges
  - Especially in delivering high value, high performance AM hardware
- NASA has dual roles
  - Drive and foster AM technology research and development in support of broad industry adoption and industrialization
  - Develop protocols for spaceflight hardware certification for access to space that can safely meet mission objectives

Today's focus

Why AM makes sense for Propulsion Components

Category	Traditional Manufacturing	Initial AM Development	Evolving AM Development
Design and Manufacturing Approach	Multiple forgings, machining, slotting, and joining operations to complete a final multi-alloy chamber assembly	Four-piece assembly using multiple AM processes; limited by AM machine size. Two-piece L-PBF GRCop-84 liner and EBW-DED Inconel 625 jacket	Three-piece assembly with AM machine size restrictions reduced and industrialized. Multi-alloy processing; one-piece L-PBF GRCop-42 liner and Inconel 625 LP-DED jacket
Schedule (Reduction)	18 months	8 months (56%)	5 months (72%)
Cost (Reduction)	$310k	$200k (35%)	$125k (60%)

Cost comparison for a 156kN (35,000 lbf) Bimetallic Rocket Combustion Chamber in 2020 USD

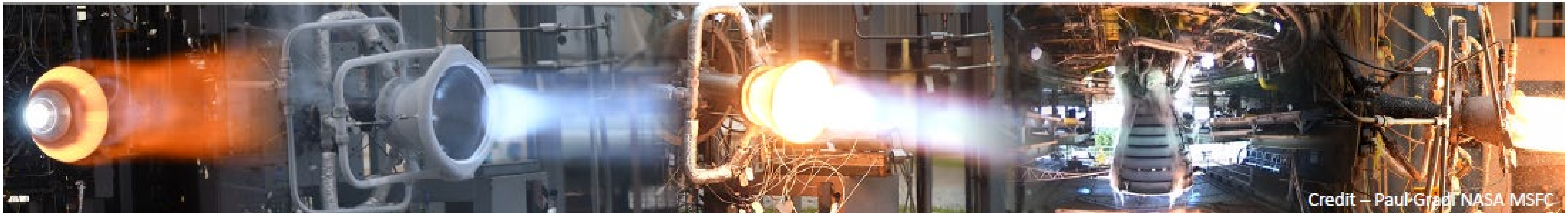
Reference: F. Kerstens, A. Cervone, P. Gradl, End to end process evaluation for additively manufactured liquid rocket engine thrust chambers, Acta Astronaut. 182 (2021) 454–465. https://doi.org/10.1016/j.actaastro.2021.02.034.

NASA's AM Insertion – Liquid Rocket Propulsion System

Laser Powder Bed Fusion (L-PBF) Copper Alloys combined with other AM processes to provide bimetallic

Directed Energy Deposition

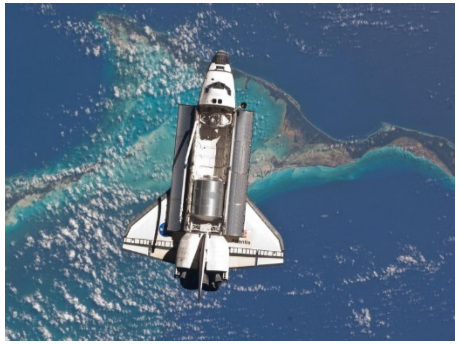
L-PBF of complex components, new alloy developments for harsh environment



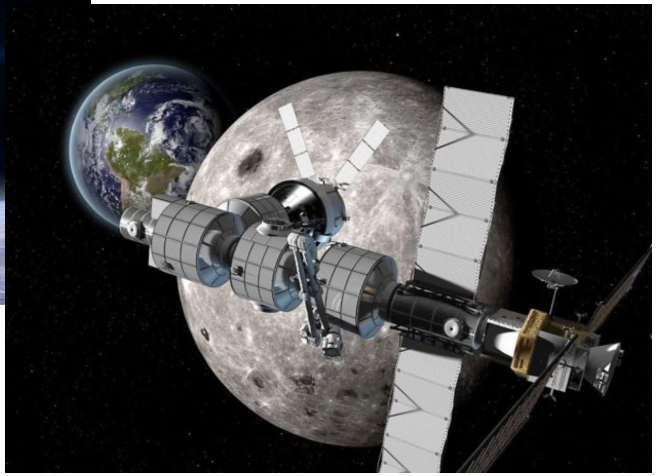
NASA's motivation for AM Standard development

- AM parts are already being use for NASA programs in critical applications
- Human exploration of space, especially deep space, requires <u>extreme</u> reliability

Low Earth Paradigm

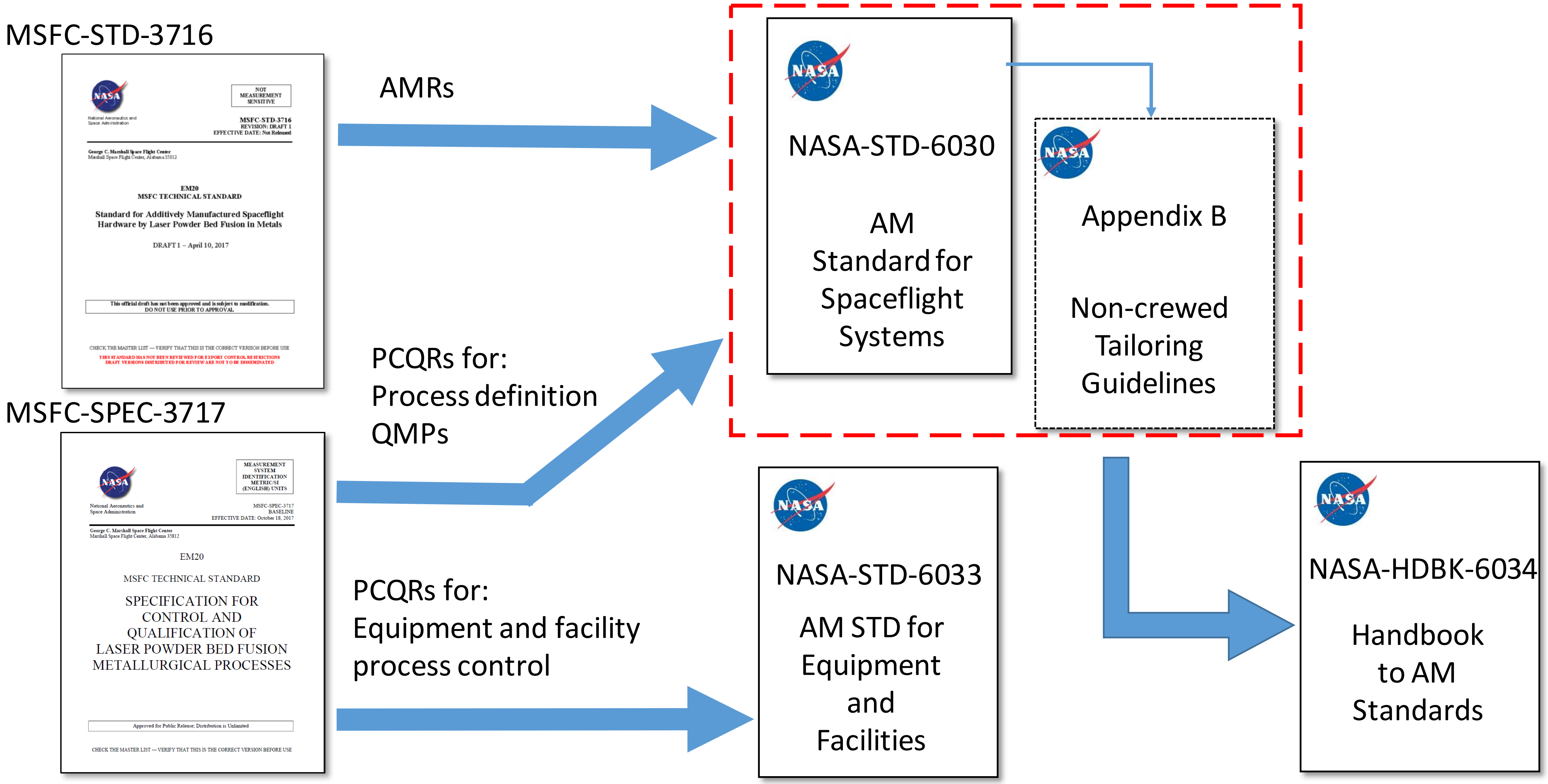


Deep Space Paradigm



250 miles vs 83,000,000+ miles
15-30 year life vs 50 to 100+ years
Replacement parts vs Limited replacement parts
Safe haven of earth vs no safe haven

New Agency Document Structure

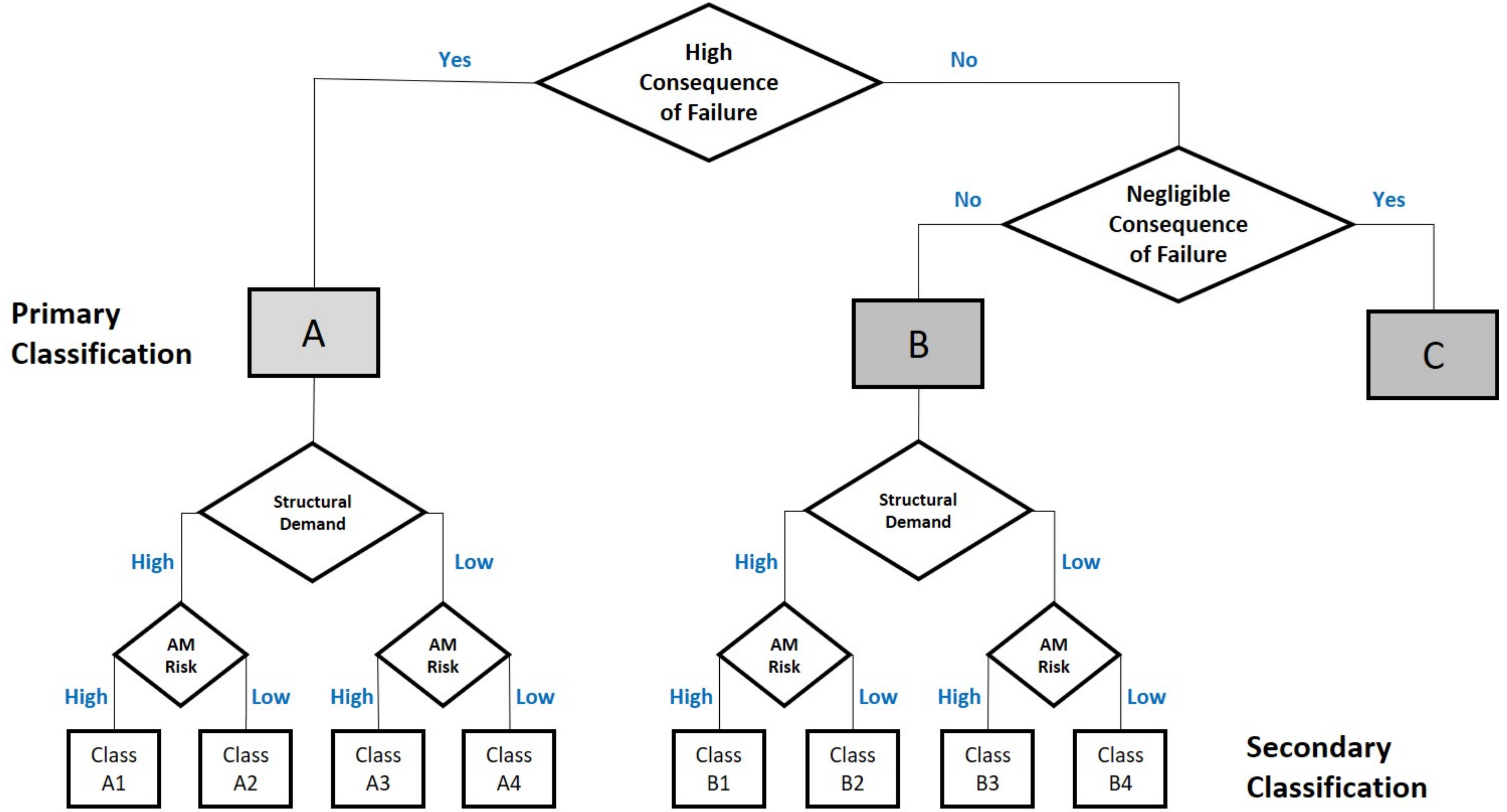


Applicability

			Class		
Category	**Technology**	**Materials Form**	**A**	**B**	**C**
Metals	L-PBF	Metal Powder	X	X	X
	DED	Metal Wire	X	X	X
	DED	Metal Blown Powder	X	X	X
Polymers	L-PBF	Thermoplastic Powder		X	X
	Vat Photopolymerization	Photopolymeric Thermoset Resin			X
	Material Extrusion	Thermoplastic filament			X

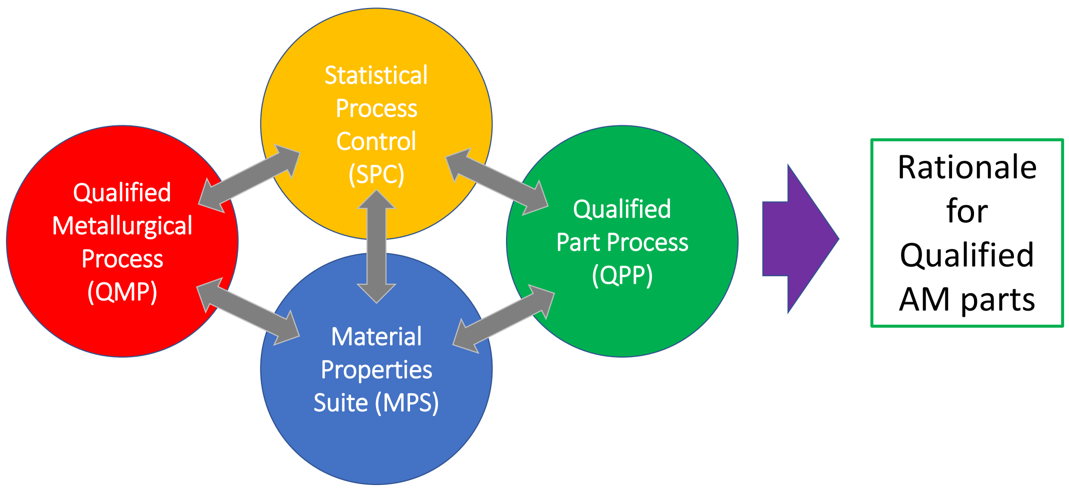
- Adaptive technologies, where the heat input can change during the manufacturing process, are not allowed
  - e.g. Electron beam powder bed fusion (E-PBF)

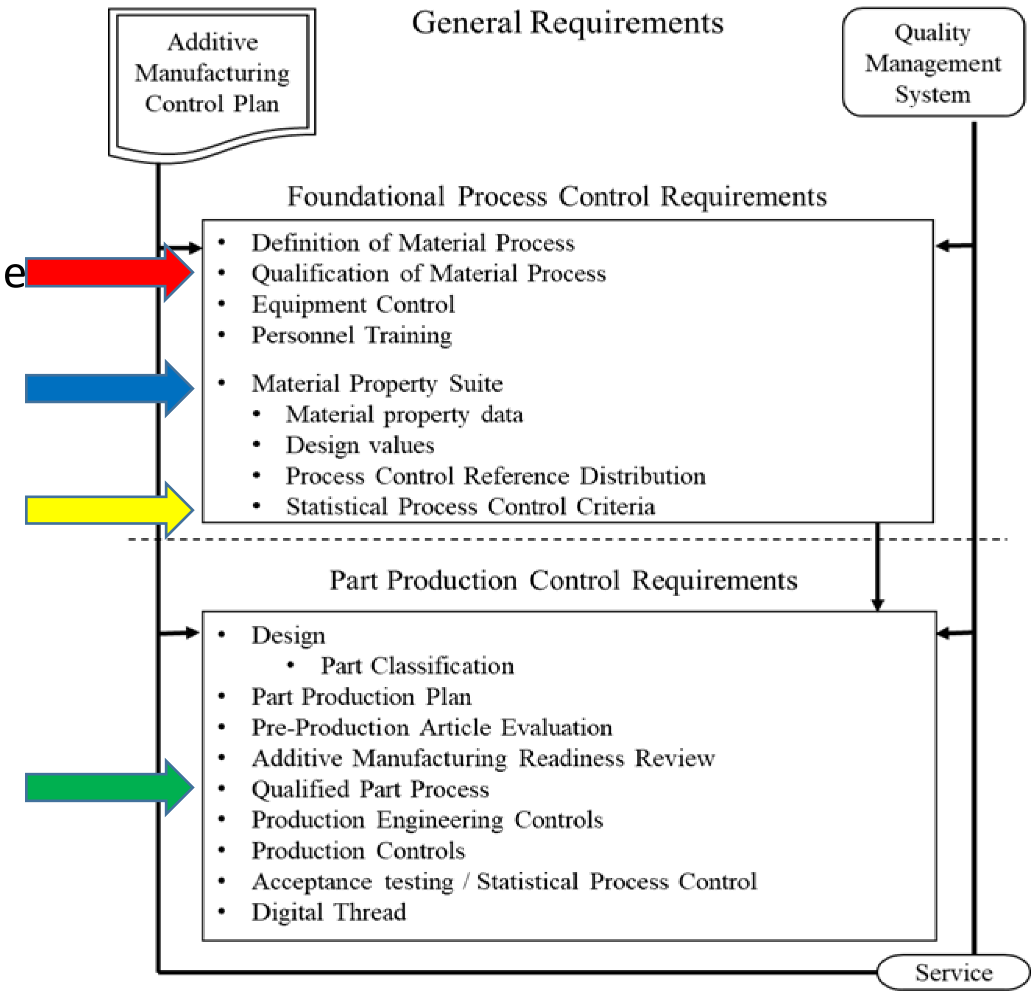
Classification



Summary of Methodology

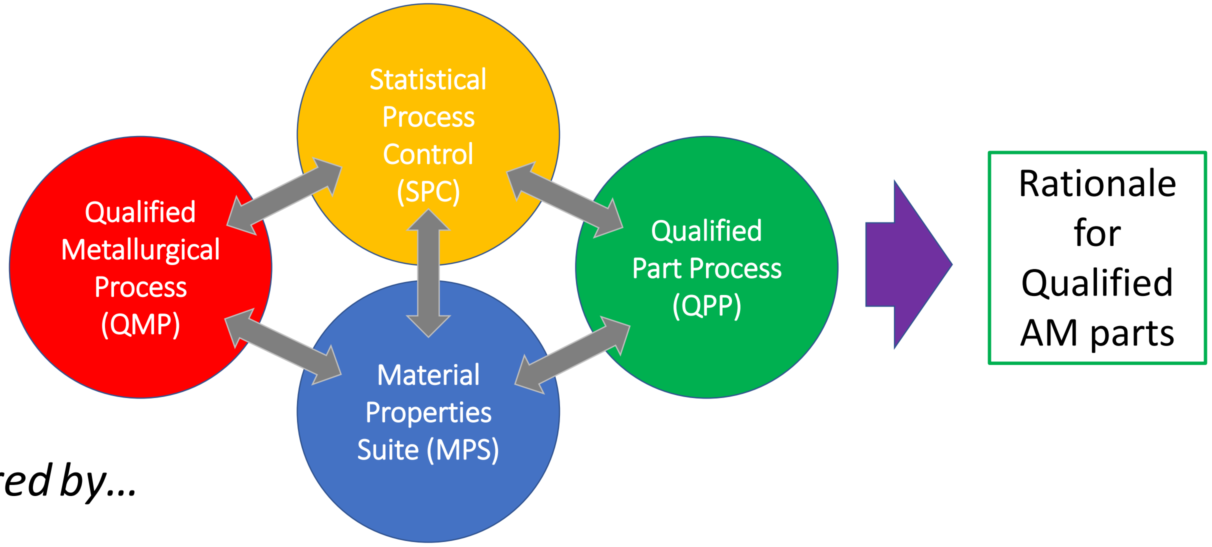
- General Requirements
  - Additive Manufacturing Control Plan (AMCP) and Quality Management System (QMS)
  - Backbone that defines and guides the engineering and production practices
- Foundational Process Control Requirements
  - Includes the requirements for AM processes that provide the basis for reliable part design and production
- Part Production Control Requirements
  - Includes design, assessment controls, plans (PPP), preproduction articles and AM production controls





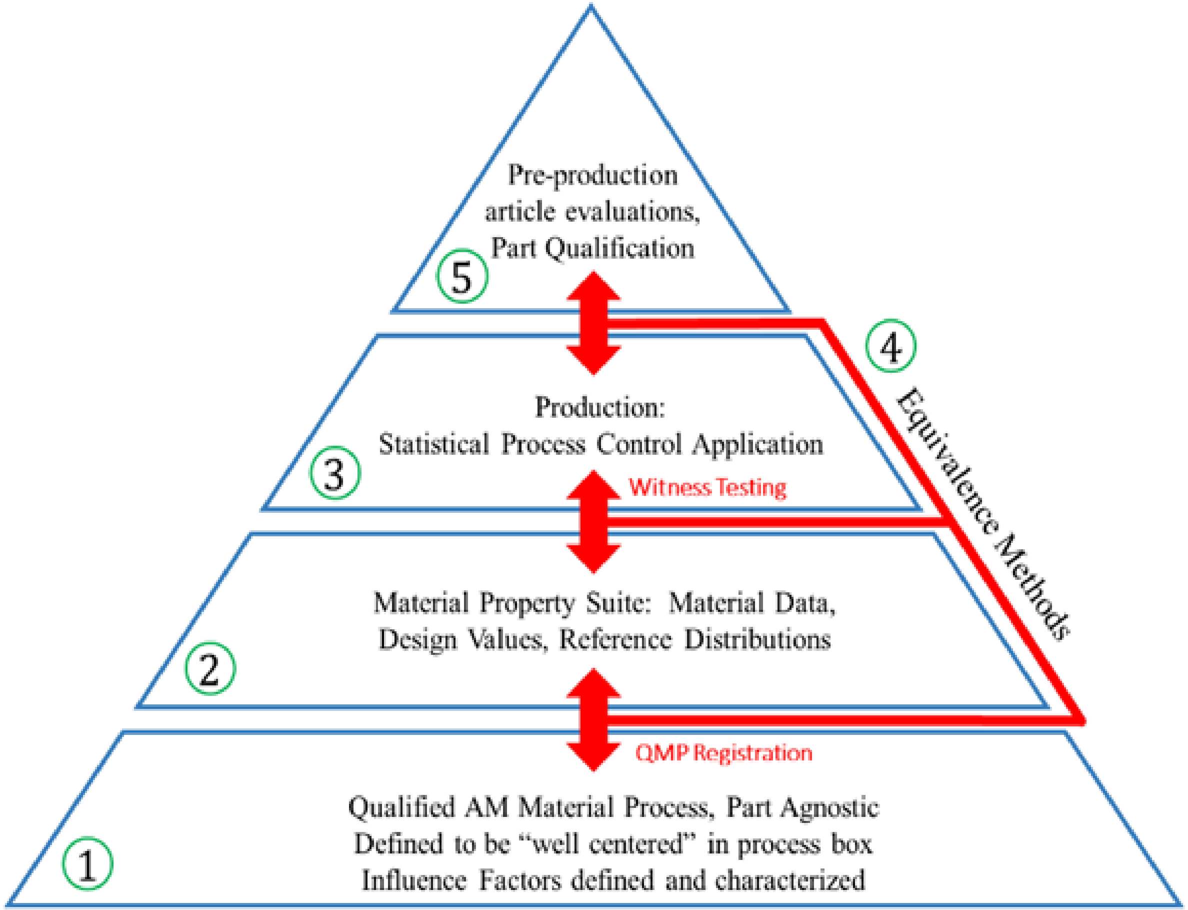
QMP: Qualified Material Process

- Begins as a Candidate QMP
- Defines aspects of the basic, *part agnostic*, fixed AM process:
  - Feedstock Controls
    - What you are building with
  - Fusion Process
    - How a machine operates
  - Thermal Process
    - Control what evolves your material state
- Qualification of the Candidate Material Process
  - Establishes a QMP: Qualified Material Process
  - Requirements vary based on classification
- Enabling Concept
  - Machine qualification and re-qualification, *monitored by…*
  - Process control metrics, SPC, *all feeding into…*
  - Design values



- AM machine and process are indelibly linked:
  - Step 1: Define a candidate process
  - Step 2: Qualify the candidate process to well-defined metrics

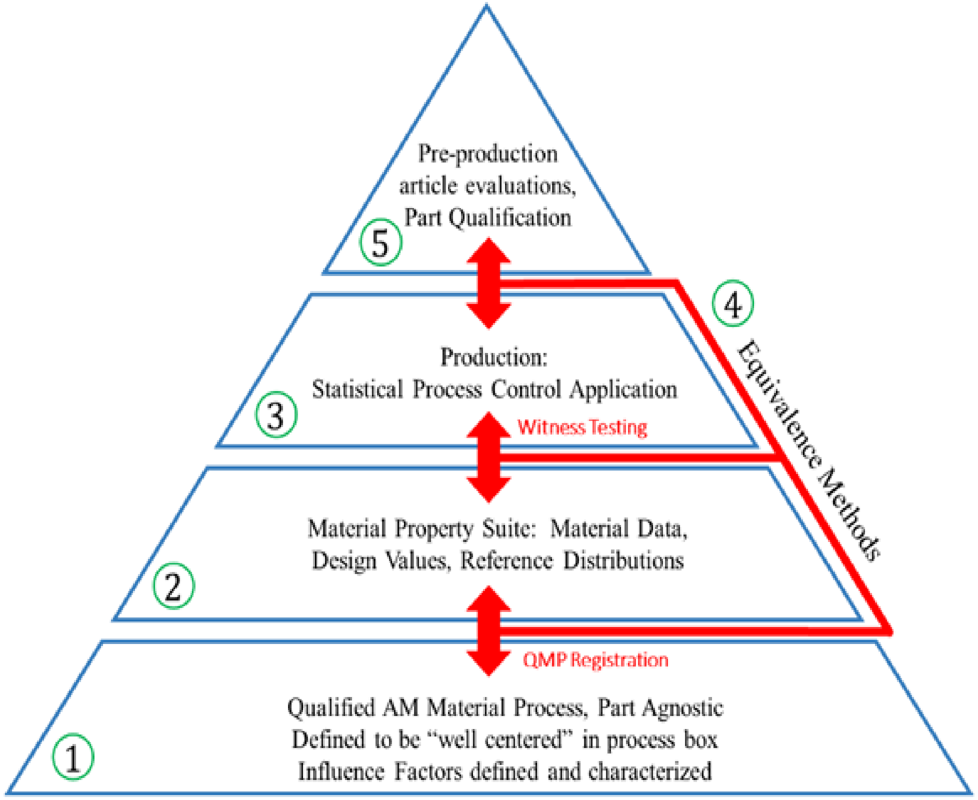
The QMP becomes the Foundation!



Material Properties

The Material Property Suite (MPS) consists of four inter-related entities:

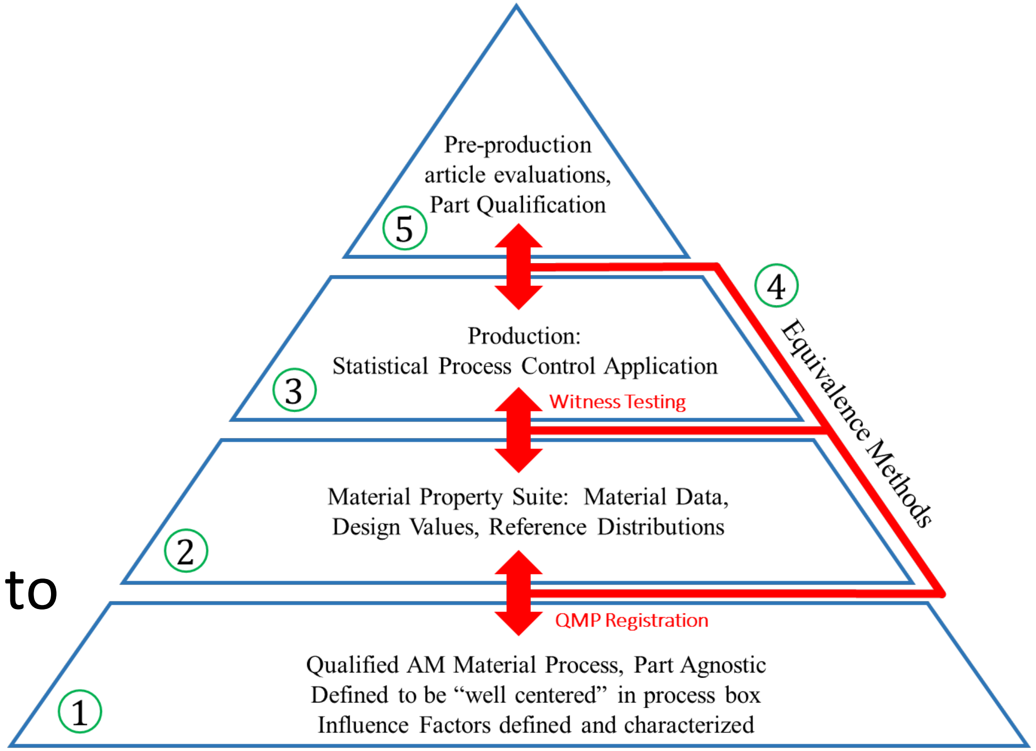
1. Data Repository
2. Design Values
3. Process Control Reference Distribution (PCRD)
4. SPC acceptance criteria for witness testing



Material Properties – SPC

Statistical process controls are important in sustaining certification rationale

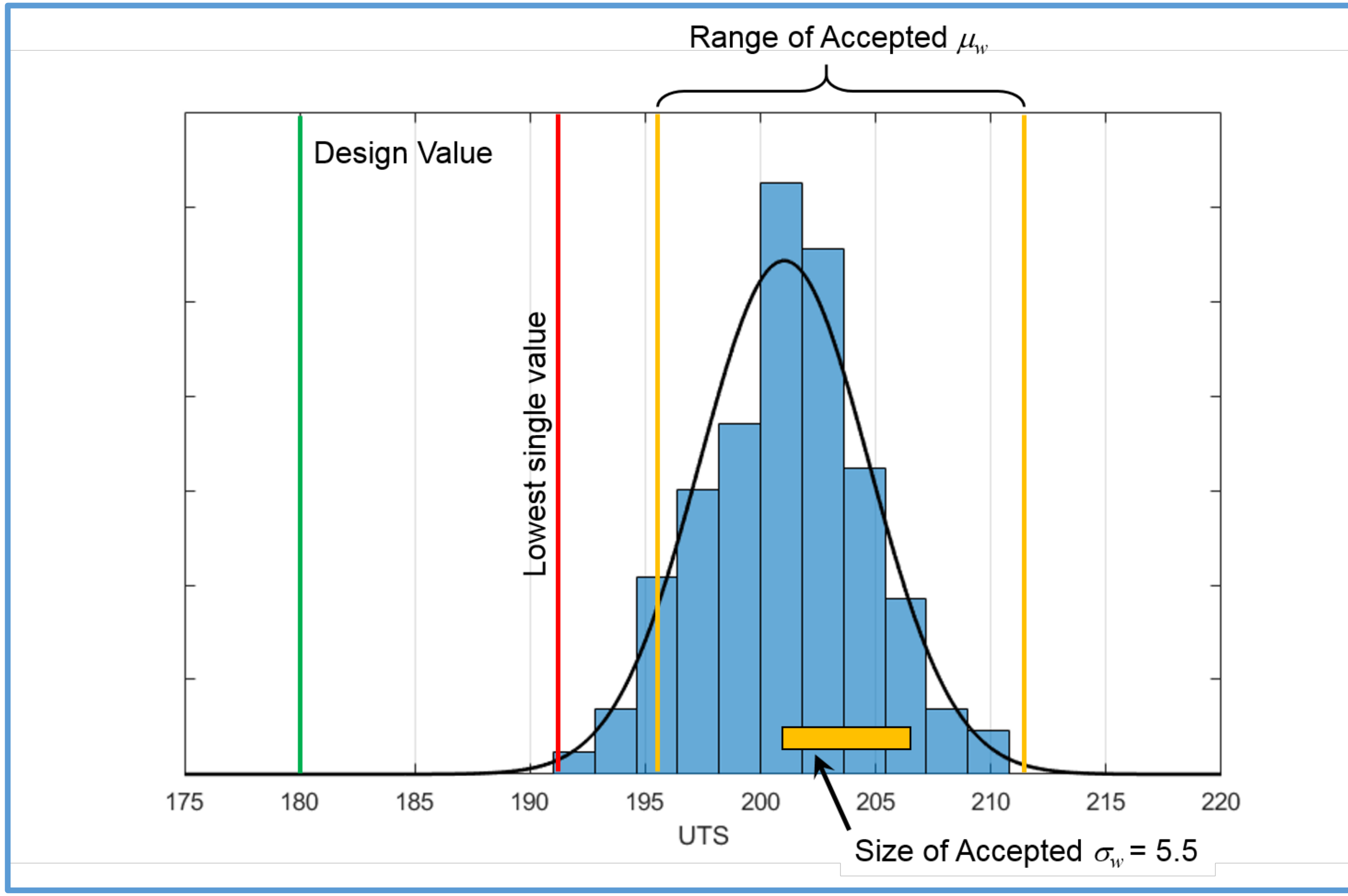
- *Statistical equivalency evaluations* substantiate design values and process stability build-to-build
  a) Process qualification
  b) Witness testing
  c) Integration to existing material data sets
  d) Pre-production article evaluations
- Equivalency of material performance is an anchor to the structural integrity rationale for additively manufactured parts



The dark and scary place most manufacturers are NOT used to operating....

Material Properties Suite – PCRD and SPC Criteria

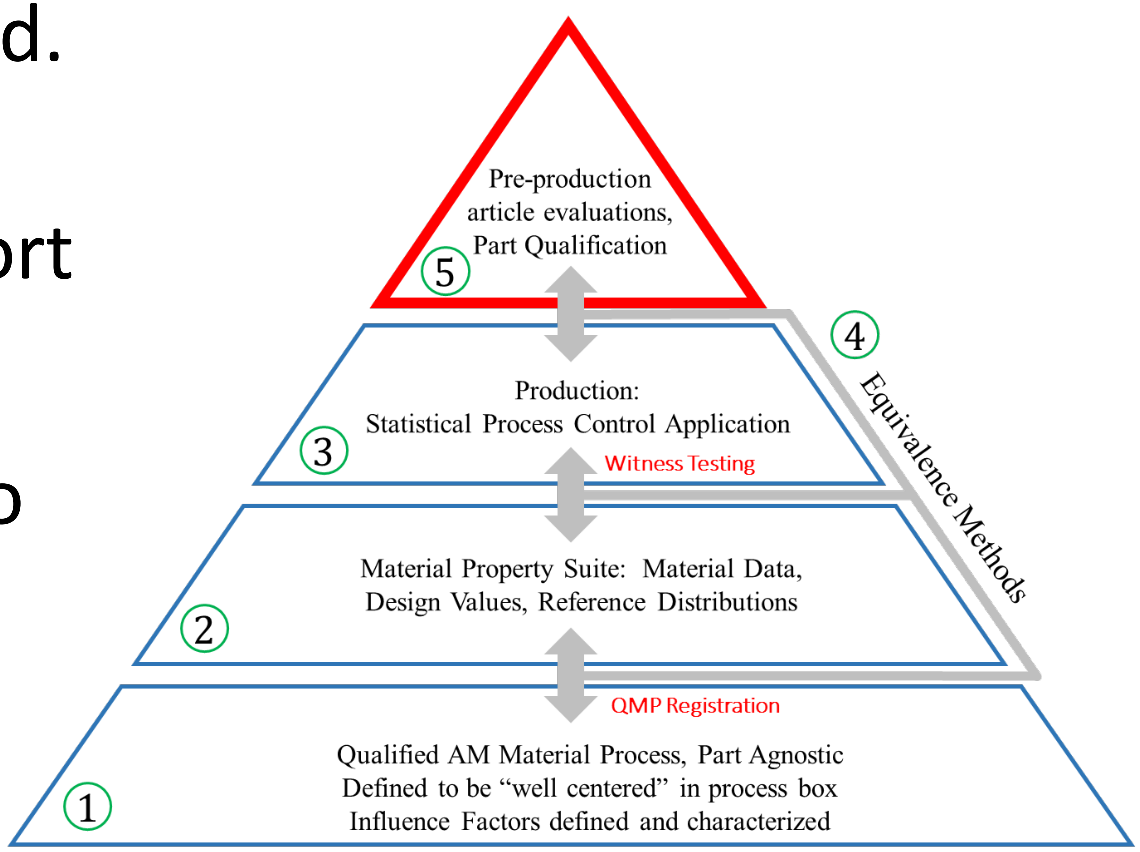
- Witness test acceptance is **not** intended to be based upon design values or "specification minimums"
- Acceptance is based on witness tests reflecting properties in the MPS used to develop design values
- Suggested approach
  - Acceptance range on mean value
  - Acceptance range on variability (e.g., standard deviation)
  - Limit on lowest single value



Foundation Complete!!

A basis to begin designing AM parts with certification intent is feasible once the foundation is laid.

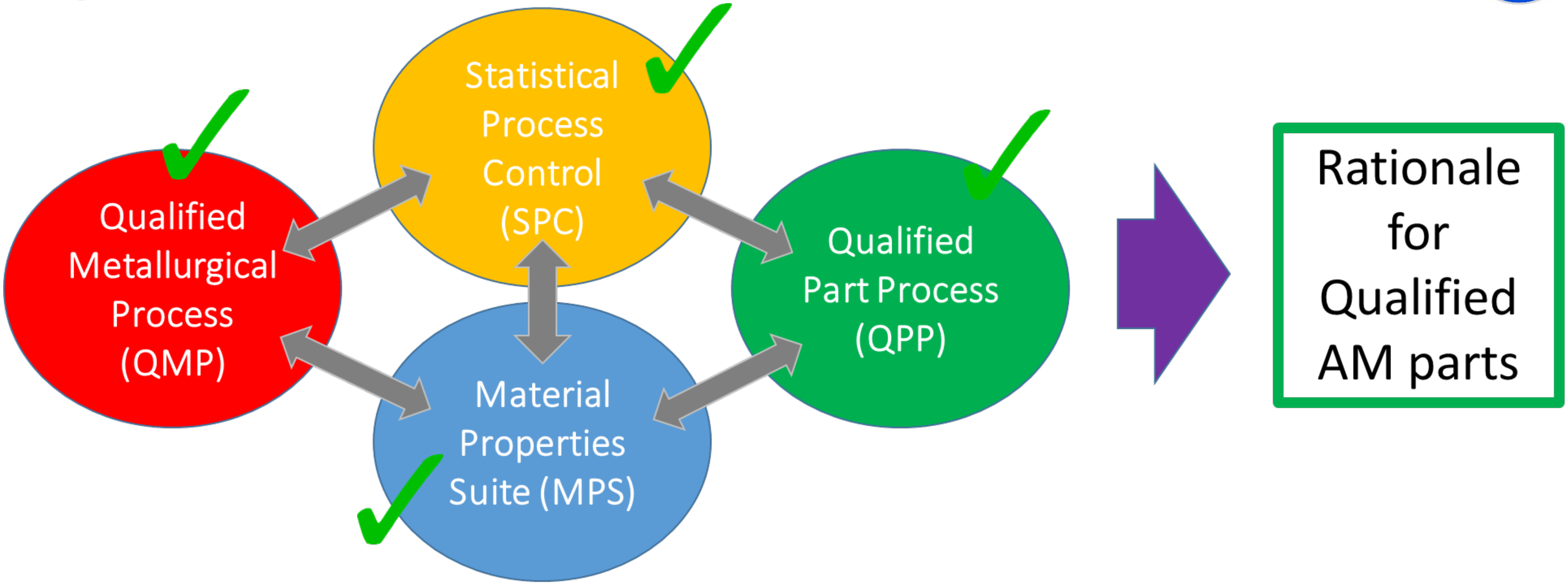
Foundation is now ready to support AM part development in an environment with suitable rigor to establish certification.



AM Part Production

1. Follow the plan, always, with no short-cuts
2. Do not change a Qualified Part Process without re-qualification
3. Efficiency in process monitoring is critical to minimize the inevitable disruption
   - Witness tests can take considerable time to complete
   - Track the performance of each machine using all available metrics by control chart
   - In-process monitoring may provide early warning of changes in machine performance
4. Emphasize the importance of inspection for every part
   - Not just NDE, but visual inspection of as-built conditions
   - Watch for changes in part appearance – colors, support structure issues, witness lines/shifts
5. Consider systemic implications for all non-conformances

Key AM Qualification Concepts



Part reliability rationale comes from the sum of both in-process and post-process controls, weakness in one must be compensated in the other

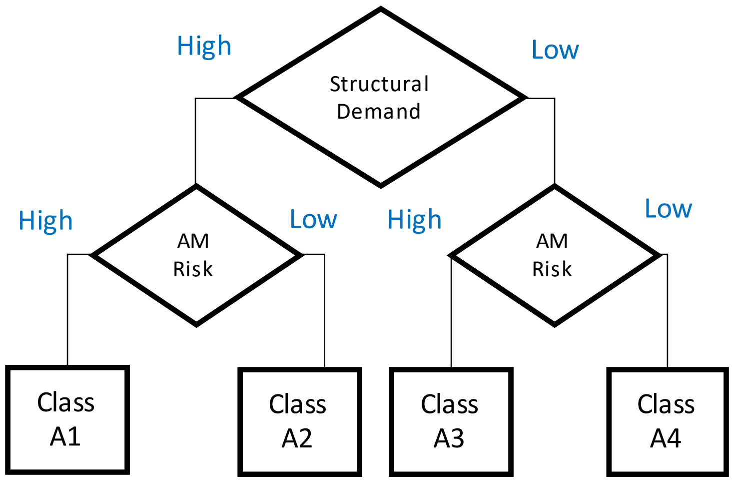
Reusability of AM Hardware

- Advantage: NASA-STD-6030 is rigorous
  - One of this standards key strengths is its reliance on material engineering equivalence
    - Methodology for evaluating the quality of AM materials that acknowledges the broad range of characteristics that must be assured for an alloy to meet all of its expectations.
    - The enabler that allows the AM material ecosystem to remain healthy and self-consistent in the face of sensitive processes with a multitude of known and unknown failure modes.
    - Requires reliable and diverse datasets, depth of knowledge in materials, good engineering judgement, and collaboration between engineering and quality assurance organizations.

Process → Structure → Property → Performance

Reusability of AM Hardware

- BUT you still need to qualify for reuse
  - A qualification test program is required for all AM parts Class A1 through B2
    - Qual test parts must be produced to a QPP
    - Parts that are mechanisms subject to NASA-STD-5017 requirements
    - Protoflight approach (no dedicated test article) not applicable
  - Fleet leader approach not a bad idea
  - Design for reuse encouraged (use secondary classification system)



Structural demand = Evaluation of how the part is loaded

AM Risk = Evaluation of the challenges of building and inspection

Fracture Control Framework for AM Parts

- Fracture control is reliant on understanding the design, analysis, testing, inspection and tracking of hardware.
  - The adaptation of state-of-the-art AM technologies introduces new and unique challenges
    - e.g. Multiple lasers and adaptive technologies
  - For AM applications the application of conventional NDE techniques is questionable
  - There is a need to produce alternate approaches through the adaptation of a Probabilistic Damage Tolerance Approach (PDTA)
    - Computational modeling for AM
    - Understanding the “Effects of defects”
    - In-situ monitoring and inspection

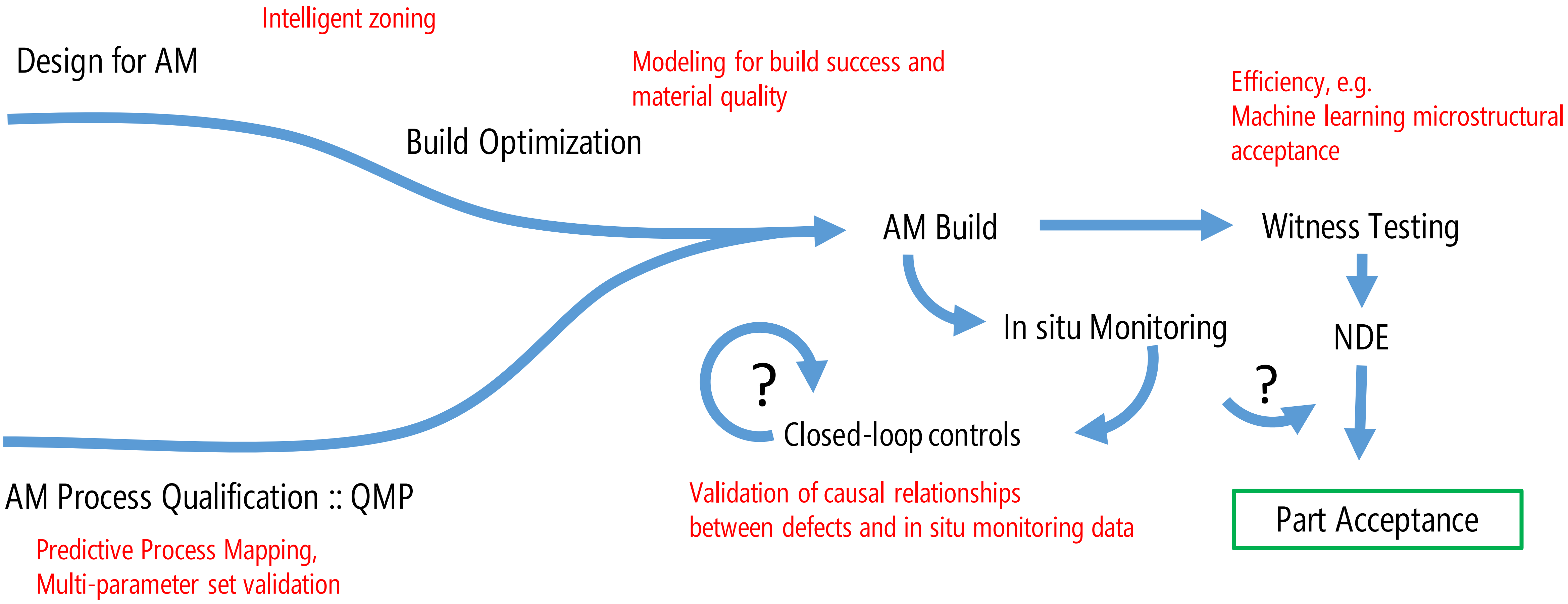
These items MUST Work together not separate

Computational Modeling of AM

- Two aspects of qualification and certification to consider:
  1. Design Certification
     - Demonstration that design meets all the requirements of the defined mission
  2. Hardware Certification
     - Demonstration that the hardware meets all the requirements of the certified design
- Opportunities for computationally-assisted qualification and certification
  - Focus primarily on augmenting the existing qualification and certification processes, NOT replacing them
  - Such methods fit into current NASA AM requirements
  - Such tools will require verification and validation
  - Leverage government-industry partnerships

Computational Modeling Opportunities

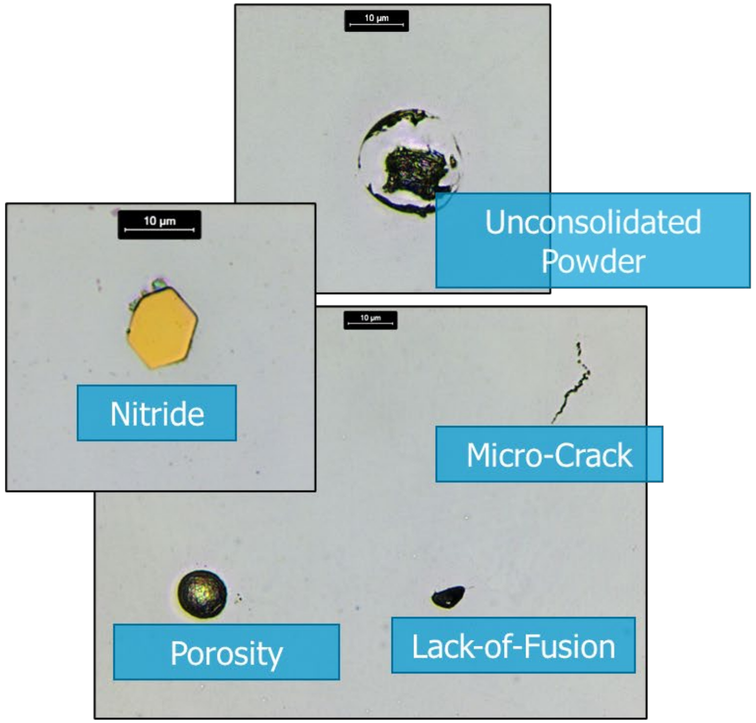
Design Cert → **Hardware Cert**

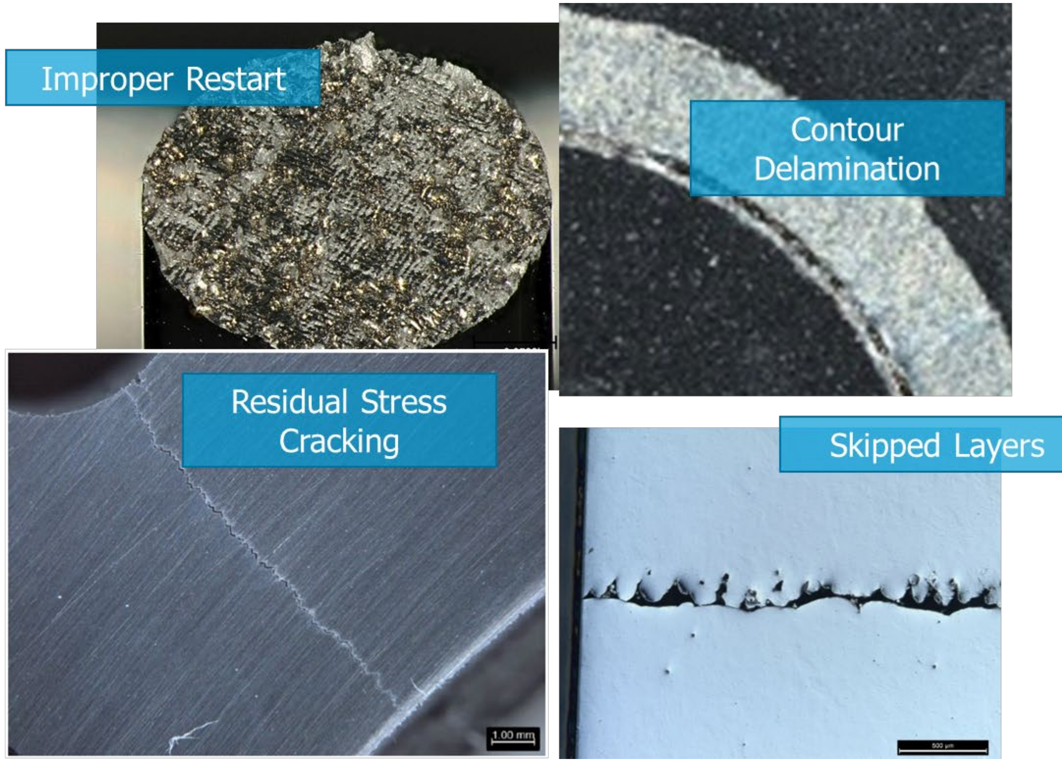


Credit: Doug Wells, NASA MSFC

Effects of Defects

- **Flaw** – an imperfection or discontinuity that may be detectable by nondestructive testing and is not necessarily rejectable.
- **Defects** – one or more flaws whose aggregate size, shape, orientation, location, or properties do not meet specified acceptance criteria and are rejectable.



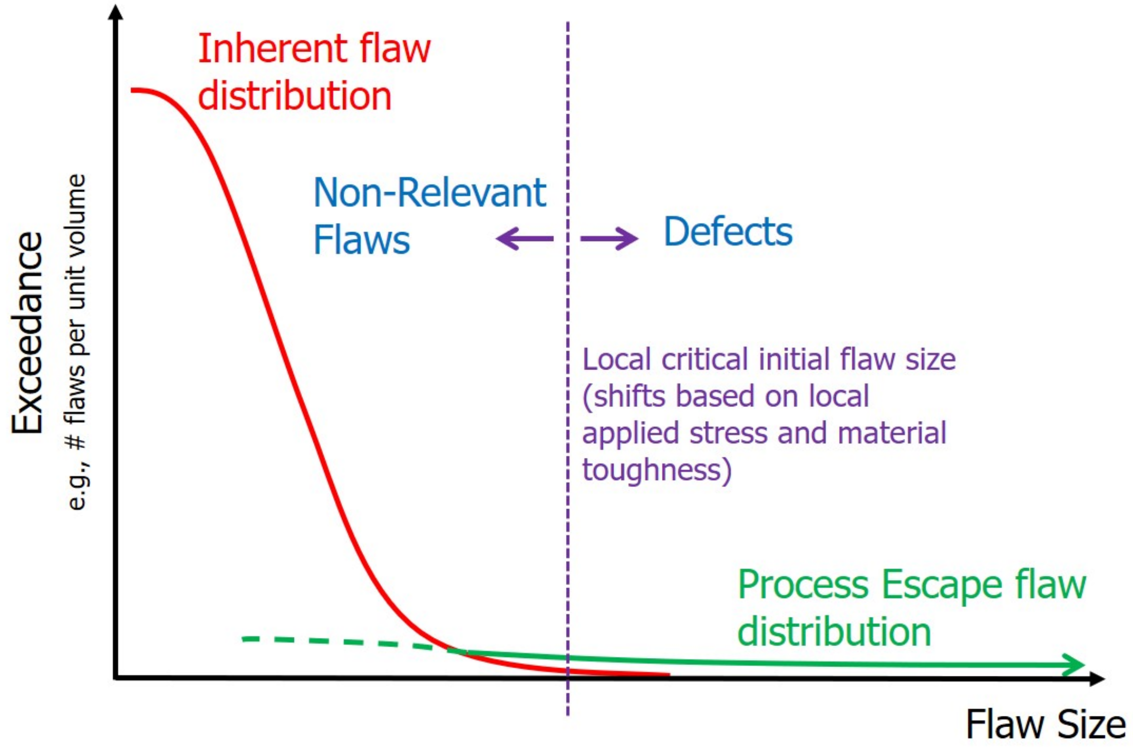


Flaws in AM fall into two categories

1. **Inherent flaws** – Flaws that are representative of the characterized nominal operation of a qualified AM process.
2. **Process Escape flaws** – Flaws that are not representative of the characterized nominal operation of a qualified AM process.

Effects of Defects

- Current NESC Assessment
  - Phase 1: Understanding inherent defects
    - Catalogue and understand the physical cause and characteristics of defects in AM processes through expert solicitation and literature review.
    - Investigate methodologies to characterize the rates of occurrence as a function of size for inherent defects for a given AM process, including operations at the defined edge of the process window.
    - Investigate methods of evaluating the inherent defect state throughout the AM process window through parameter design of experiments or geometry-based process challenge builds.



Effects of Defects

- Future planned work
  - Phase 2: Using process controls to control inherent defect populations
    - Determine the feasibility of using process controls (and limitations thereof) to govern the population of inherent defects in AM hardware through the controls of NASA-STD-6030, in-situ monitoring, or other means.
    - Determine the feasibility and limitations of incorporating the inherent defect population into fatigue design values.
  - Phase 3: Understanding Rogue defects
    - Determine feasibility of Process Failure Modes and Effects Analysis (P-FMEA) to understand the characteristics and occurrence likelihood of potential rogue AM defects.
    - Determine the feasibility of using process controls to limit the population of rogue defects in AM hardware through the controls of NASA-STD-6030, in-situ monitoring, or other means.
    - Map the physical cause of rogue defects for a given AM machine/process against available/potential in-situ monitoring techniques to evaluate the ability to preclude the defects or bound their size during the process.
    - Investigate practical methods to apply the above knowledge of defect state to practical PDTA to inform failure risk.

Initial effort already started in partnership with the ASTM Center of Excellence

In-situ Monitoring

- NASA-STD-6030 requires
  - Quantitative NDE for class A parts
  - NDE for process control for class B parts

  Must meet requirements of NASA-STD-5009

  - In-situ monitoring must be qualified in manner analogous to other NDE techniques
- Two main functions of in-situ process monitoring:
  - <u>Process Control</u>
    - Real-time warnings of build problems
    - Check for process drift
    - Monitor effects of parameter changes
  - <u>Part Quality</u>
    - Quantitative analysis
    - Requires correlations between indications, physics of the process and actual defects
    - Need to know probability of detection

In-situ Monitoring

- Challenges to using in-situ monitoring:
  - Indirect defect observations will require an understanding of the physics
  - Current certification approach requires a locked process
    - For real-time changes a new approach is needed
  - Current certification approach does not accommodate the use of adaptive systems
    - Creates two issues for verification
      1. Verify the senor performance, algorithm and machine response (control system)
      2. Verify the physics – does controlling this parameter result in a good part?

Conclusions

1. Certification rationale is most heavily rooted in the foundational controls
2. Part Planning must confirm the foundation produces a good part consistently
3. Part production follows a fixed process with statistical process controls
4. Going forward NASA must develop a Fracture Control Framework for AM Parts which includes the adaptation of a Probabilistic Damage Tolerance Approach (PDTA)
    - Computational modeling for AM
    - Understanding the "Effects of defects"
    - In-situ monitoring and inspection